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GEOLOGIC STRUCTURE OF THE TALTAL AREA, NORTHERN CHILE, IN RELATION TO THE EARTHQUAKE OF DECEMBER 28, 1966

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ABSTRACT

The Taltal area, which lies within the coastal cordillera of northern Chile, is dominated by a group of major active faults that cut a eugeosynclinal section of predominantly Jurassic andesites overlying Paleozoic metamorphic and plutonic rocks and intruded by Late Mesozoic plutons. The Atacama fault, a suggested regional strike-slip fracture parallel to the coastline, has been obliquely cut and left-laterally offset 10 km by the Taltal fault, which passes through the town of Taltal. Three distinctive features were found to be consistently offset 10 km by the Taltal fault: the easternmost strand of the Atacama fault, an intrusive contact, and a unique volcanic unit. Former continuity of the Atacama fault through the Taltal region is proposed, and subsequent disruption by the Taltal fault appears to have caused major structural readjustments in the still-active Atacama fault zone.

The tentative offshore epicenter and aftershock distribution of the December 28 earthquake are not directly correlative with faults that have been mapped in the nearby on-shore areas; this lack of correlation is not surprising in view of the suggested depths of hypocenters in the lower crust or upper mantle.

Introduction

The Taltal earthquake of December 28, 1966, and its aftershocks occurred in a part of northern Chile for which there is limited published geologic information to assist in interpreting the seismic events. St. Amand and Allen (1960) suggested the importance of transcurrent faults in the tectonic framework of northern Chile, and had specifically proposed the existence of a major north-trending active strike-slip fault—the Atacama fault—parallel to the coastline for more than 1000 km and extending through the Taltal region. Other workers had earlier recognized parts of this fault zone, particularly south of Taltal (Ruiz, 1943; Segerstrom *et al*, 1960; Bowes *et al*, 1961; Segerstrom and Ruiz, 1962), but no documentation of large-scale lateral offsets along the Atacama fault has as yet been put forth. Indeed, even the predominance of strike slip has not been demonstrated, inasmuch as St. Amand and Allen relied primarily on suggestive evidence such as "rift topography," linearity, and length (Allen, 1965).

Because of the absence of conclusive evidence concerning the nature of the Atacama fault zone, the author spent six weeks in Chile during August and September of 1966 for the purpose of outlining a broad field study of the fault, to encompass its continuity, sense of displacement, and regional tectonic significance. Field efforts during this preliminary period were concentrated near Taltal (Figure 1) because the fault was particularly well exposed and accessible there; furthermore,

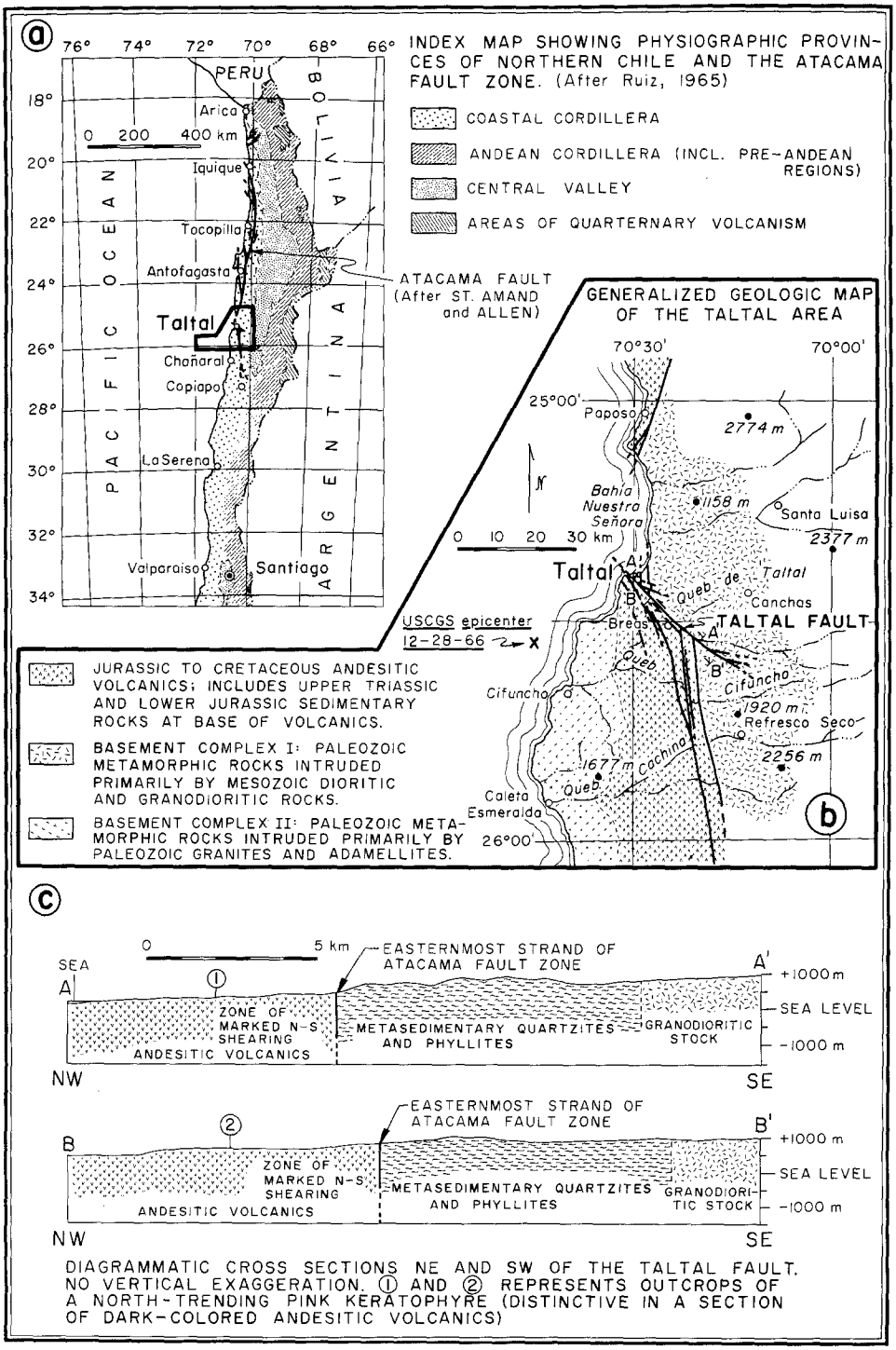

FIG. 1. Index and geologic maps.

the continuity of the two major segments extending north and south from Taltal was open to question and offered an attractive initial problem. St. Amand and Allen (1960) had suggested that a single major north-trending fault zone (the Atacama fault) had itself been offset by a northwest trending sinistral fault (the Taltal fault) that passed essentially through the town of Taltal. On the other hand, Bowes *et al* (1961) argued that the complications in the Taltal area were caused by the intersection of two distinct and slightly divergent north-trending fault zones. In an attempt to resolve this issue the author endeavored to find field evidence of lateral offset along the Taltal fault by detailed field mapping. It was this very area that subsequently was hit by the earthquake of December 28th, and the preliminary results on the geologic structure are presented herein because of their pertinence to this event. This contribution is considered as a companion paper to the accompanying articles by Lemke *et al* (1968) and Pitt and Ellis (1968), which describe the geological and seismological aspects of the earthquake itself.

Regional Geology

General features. The Taltal area lies within the coastal cordillera of northern Chile, which is separated from the main chain of the Andes by an upland area analogous to the Central Valley of southern Chile. The coastal ranges mark the western marginal area of the great Mesozoic Andean geosyncline, so that these ranges expose moderate thicknesses of predominantly Jurassic volcanic accumulations overlying a basement terrane of Paleozoic metamorphic and granitic rocks. The basement and geosynclinal rocks have in turn been intimately intruded by Late Mesozoic granitic rocks, and the entire sequence has been moderately folded and intensely faulted. Tectonic deformation is continuing into the present epoch as indicated by abundant Quaternary fault scarps along the Atacama fault and its branches, although the relationship between this faulting and the earlier tectonic history of northern Chile is obscure.

The broader tectonic features of the region are illustrated by crustal profiles across the continental border approximately 2° north of Taltal. Profiles constructed from results of both off-shore and on-shore geophysical exploration (Woollard, 1960; Fisher and Raitt, 1962; Hayes, 1966) show a pronounced crustal thickening from the oceanward flank of the Peru-Chile Trench to the axis of the Andes. Lomnitz (1962) emphasizes manifestations of the current tectonic activity at this continental borderland: the active volcanism in the Chilean Andes, the high seismicity of northern Chile, the steepness of the east-west gravity gradient, and the steep topographic gradient from the heights of the Andes to the depths of the Peru-Chile Trench.

Rock descriptions and distribution. A complex of quartzites, argillites, phyllites, and mica schists probably represents the oldest rock unit of the area. These rocks have usually been assigned a Late Paleozoic age on the basis of comparison with similar rocks of the Toco Formation that are exposed a few hundred kilometers to the north, where Wetzel (1927) found Permo-Carboniferous plant fossils. In Figure 1b, two principal basement terranes have been distinguished, both of which include these presumably Paleozoic metamorphic rocks, but which have been intruded by two distinct suites of granitic rocks.

Basement I is exposed east of the Atacama fault zone and comprises the Upper Paleozoic metamorphic rocks intruded by granitic rocks with some compositional variance, but including diorite and granodiorite. Similar granitic rocks elsewhere in Chile are associated with Late Jurassic and Middle Cretaceous batholithic suites (Ruiz *et al*, 1961; Levi *et al*, 1963). Bowes *et al* (1961) adopt a Middle Cretaceous age for these granitic rocks in the Taltal area, although no age determinations have been made on samples of this suite from the immediate region.

In Basement II, which crops out in the coastal area south of Taltal, the Upper Paleozoic metamorphic rocks are intruded primarily by light gray, medium- to coarse-grained, quartzose granites and ademellites. These intrusive rocks are dated as definitely pre-Jurassic on the basis of stratigraphic arguments (F. Ortiz, personal communication; Ruiz *et al*, 1961) and as Paleozoic (340 $\pm$ 40 my; 280 $\pm$ 50 my) on the basis of lead-alpha radiometric dating (Levi *et al*, 1963). Perthitic feldspars, biotite and abundant quartz characterize these granitic rocks.

A eugeosynclinal section of Jurassic to Cretaceous andesitic flows and breccias, several thousands of meters thick, crops out over a wide area south of Taltal. The volcanics are referred to as the "La Negra" formation and have a regional eastward to southeastward dip. Triassic(?) conglomerates and felsic tuffs and Lower Jurassic marine beds underlie the volcanic section in part; exposures can be seen along the western volcanic contact south of Taltal (Ruiz *et al*, 1961).

The andesites vary in texture, color and degree of propylitization but, for the most part, they constitute a monotonous sequence. They are significantly bounded by the easternmost strand of the Atacama fault zone, both south and immediately north of the Taltal fault. South of the Taltal fault the volcanics are bounded by the Atacama fault zone for more than 30 km. Field mapping by the writer east of the Atacama fault zone differs from that of Bowes *et al* (1961), which was based heavily on photogeologic interpretation.

Whether or not the bounding of the "La Negra" formation in the Taltal area by the Atacama fault is of fundamental regional importance will only be determined after further mapping, since there are complications in two zones. Near Paposo the volcanics are partly bounded on the east by the fault, but within a fault slice south of the town, small dioritic bodies intrude the volcanics, while migmatites occur east of the fault zone. Also, there are volcanic outcrops within the area of splaying of the Taltal fault at its southeastern extremity, where the volcanics are judged to be part of a roof pendant.

Structure

In his summary of the regional geology of Chile, Zeil (1964) emphasizes the fact that fractures more than flexures characterize the structure of the Chilean cordilleras. This generalization is borne out in the Taltal area, where the faults are the most important structural elements. Major folding is limited to the Paleozoic metamorphic rocks.

Traces of the major faults of the region as mapped by the writer are shown in Figure 1b. Since the Atacama and Taltal faults were of prime concern, minor faults outside the area of main interest were not traced. In the inland block northeast of Taltal, Bowes *et al* (1961) have mapped minor faults with a northeasterly trend;

faults with a northwesterly trend are shown by these authors in the coastal region south of Taltal.

In the Taltal area, the main elements of the fault pattern are: (1) a north-trending zone of faults south of Taltal whose western strands arc northwestward; (2) a northwest-trending fault zone (Taltal fault) which abruptly truncates the eastern strands of the above-mentioned zone; (3) a north-trending zone of faulting which is located immediately east of Taltal and which projects northward into the sea toward Paposo; and (4) a north-trending fault zone which projects southward into the sea south of Paposo.

The nomenclature of St. Amand and Allen (1960) has been followed in this paper to designate groups (1), (3) and (4) as segments of the major Atacama fault zone—a nomenclature necessarily implying their former continuity. The segment south of the Taltal fault extends some 200 km to the Copiapó region and had locally been called the El Salado, Manto Atacama, or Manto Verde fault (e.g., Segerstrom *et al*, 1960). Bowes *et al* (1961) restrict the term Atacama fault to this segment. Segment (4), which reportedly can be traced northward approximately 450 km until it branches out to sea south of Iquique (St. Amand and Allen, 1960) is termed the Salar del Carmen fault by Bowes *et al* (1959) and is herein termed the Salar del Carmen sector of the Atacama fault.

The interpretation that segments (1), (3) and (4) are parts of a single major fault zone differs from that of Bowes *et al* (1961), who view the structural complications near Taltal as the result of the intersection of two distinct fault zones having opposing senses of lateral displacement. They argue that the deformity and northwestward curving of their "Atacama fault" (segment 1) are caused by drag effects of right-lateral movement along the Salar del Carmen fault (segment 4). Thus the problem of whether the Atacama fault is a feature of major regional tectonic significance, comparable to the San Andreas fault of California, depends partly on whether its continuity can be demonstrated through the Taltal area.

Evidence is presented herein for 10 km of left-lateral movement along the Taltal fault, indicating that the Atacama fault zone is indeed offset and probably once was continuous with the segment near Paposo. In attempting to discover displacements across the Taltal fault, three features were found to be left-laterally offset; each feature has been displaced approximately 10 km. The information presented below is diagrammatically shown in Figure 1c.

South of the Taltal fault, the easternmost strand of the Atacama fault zone is near-vertical, north-trending, and juxtaposes sheared andesitic volcanics against quartzites and phyllites. To the east of this strand there are no major north-south shear zones. Near Taltal, on the northern side of the Taltal fault, an identical relationship was found. Zones of strong north-south shearing within andesitic volcanics can be seen. The easternmost fault separates sheared andesites from quartzites and phyllites.

East of the Atacama fault zone, both to the north and south of the Taltal fault, the quartzites and phyllites are intruded by granodioritic and dioritic stocks. An intrusive contact was found to be cut by the Taltal fault and displaced 10 km. Also, a pink keratophyre, distinctive in a section of dark andesites, was mapped immediately east of Taltal; the offset continuation of this north-striking unit was found

offset 10 km southeast along the Taltal fault. The presence of highly sheared rocks and sub-horizontal slickensides along the Taltal fault, coupled with the consistent offset of the three features mentioned above, provide strong evidence for the left-lateral offset of the Atacama fault zone. It is significant that this demonstrable displacement of 10 km is the largest lateral displacement noted to date in northern Chile.

Inasmuch as the Atacama fault zone was probably once continuous through the Taltal area and subsequently offset by the Taltal fault, it is clear that throughgoing contemporary displacements along the Atacama fault are constrained. The fault is by no means inactive, as attested by abundant Quaternary fault scarps along its traces, both north and south of the Taltal fault, and so strain accumulation along the Atacama fault zone must be continuing. It is interesting to note that if the strain has had a significant lateral component, which has not been proved, one of three adjustments in the fault zone would be likely in order to allow current tectonic strain to accommodate itself to the structural "knot" of the Taltal area: (1) thrusting along the general trace of the Taltal fault, (2) development of gently curving traces connecting the two major offset segments of the Atacama fault, or (3) prolongation of the truncated segments of the Atacama fault as new independent breaks across the Taltal fault. There is no indication of thrusting along the Taltal fault, but marked splaying of the Atacama fault as it approaches the Taltal fault from the south suggests that an adjustment of type (2) is probably taking place. This widening of the fault zone is of interest because the fault zone is significantly narrower along most of its course to the south. Mechanism (3) does not appear to have been effective in the on-shore area, inasmuch as no breaks can be traced across the Taltal fault, but such an adjustment could have happened beneath the Bahía Nuestra Señora. It would not be surprising if a subsea branch of the Salar del Carmen sector of the Atacama fault, once terminated by the Taltal fault, were now prolonging itself farther southwestward. In the absence of submarine topographic information, however, there is no way of evaluating this possibility.

Relation of Epicenters to Geology

Although the epicentral location of the main shock of December 28th has been the subject of much confusion and debate, there now seems to be general agreement that it lies offshore north of Cifuncho (Figure 1b). Disagreement still exists as to the depth of focus, however, with estimates ranging from 46 to 149 km. It is significant from the geological point of view, nevertheless, that the focus clearly appears to be in the upper mantle, so that a lack of obvious correlation with surficial features would not be surprising. Similarly, aftershock data compiled by Pitt and Ellis (1968) indicate depths of slightly more than 30 km, thus substantiating the probable location of the activity in the upper mantle or lower crust.

Although the epicenter of the main shock lies along a southwestward projection of segment (4) of the Atacama fault, as defined previously, distribution of the aftershocks in a divergent north-south offshore zone (Pitt and Ellis, 1968, Figure 5) leads the writer to minimize association of this earthquake with the Atacama fault. The principal epicenter also lies along the seaward projection of a northwest-trending fault passing through Cifuncho mapped by Bowes *et al* (1961), but recon-

naissance by the writer indicates that this is not a major structure. The seismic and geologic data, then, suggest a relationship with a deeper and larger scale feature of the South American continental border, perhaps with a structure involving the Peru-Chile trench. Hayes (1966) deduces crustal thinning in connection with the Peru-Chile trench and would postulate extension at the continental margin. Geologic evidence in the Taltal region, however, suggests to the writer that compressive rather than extensional stresses have been active in this on-shore area, although the fault on which this particular earthquake occurred has not been identified.

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References

Allen, C. R. (1965). Transcurrent faults in continental areas, *Royal Soc. [London] Philos. Trans.* **258,** 82–89.

Bowes, W. A., P. H. Knowles, M. Serrano C. and R. Gruenwald S. (1959). Reconnaissance for uranium in the Tocopilla area, Province of Antofagasta, Chile, *U. S. Atomic Energy Comm. RME-4534 (rev.).*

Bowes, W. A., P. H. Knowles, A. Moraga B. and M. Serrano C. (1961). Reconnaissance for uranium in the Chañaral-Taltal area, Provinces of Antofagasta and Atacama, Chile, *U. S. Atomic Energy Comm. RME-4565 (rev.).*

Fisher, R. L. and R. W. Raitt (1962). Topography and structure of the Peru-Chile Trench, *Deep Sea Res.* **9,** 423–443.

Hayes, D. E. (1966). A geophysical investigation of the Peru-Chile Trench, *Marine Geology,* **4,** 309–351.

Lemke, R. W. *et al* (1968). Geologic and related effects of the Taltal earthquake, Chile, of December 28, 1966, *Bull. Seism. Soc. Am.* **58,** 851–859.

Levi, B., S. Mehech and F. Munizaga (1963). Edades radiométricas y petrografía de granitos chilenos, *Chile Instituto de Investigaciones Geológicas, Boletín,* **14,** 42 p.

Lomnitz, C. (1962). On Andean structure, *J. Geophys. Res.* **67,** 351–363.

Pitt, A. M. and J. Ellis (1968). Preliminary report on some aftershocks of the December 28, 1966 earthquake in Northern Chile, *Bull. Seism. Soc. Am.* **58,** 843–850.

Ruiz, C. (1943). Los yacimientos de hierro de la región noroccidental de Copiapó, un tipo no descrito de yacimientos de contacto metamórfico, *Santiago, Boletín Minero,* **55,** 820–827, 906–915.

Ruiz, C. (1965). *Geología y yacimientos metalíferos de Chile,* Santiago, Instituto de Investigaciones Geológicas, 305 pp.

Ruiz, C., L. Aguirre, J. Corvalán, H. J. Rose, Jr., K. Segerstrom and T. W. Stern (1961). Age of batholithic intrusions of northern and central Chile, *Bull. Geol. Soc. Am.* **72,** 1551–1560.

Segerstrom, K., B. L. de Valenzuela and S. Mehech (1960). Cuadrángulo Chamonate, *Chile, Instituto de Investigaciones Geológicas, Carta Geológica de Chile,* **2,** (3), 42 p.

Segerstrom, K. and C. Ruiz F. (1962). Cuadrángulo Copiapó, *Chile, Instituto de Investigaciones Geológicas, Carta Geólogica de Chile,* **3,** (1), 115 p.

St. Amand, P. and C. R. Allen (1960). Strike-slip faulting in northern Chile (abstract), *Bull. Geol. Soc. Am.* **71,** 1965.

Wetzel, W. (1927). Beiträge zur Erdgeschichte der Mittleren Atacama, *Neues Jahrrbuch für Mineralogie, Geologie und Paläontologie, Bd. LVII,* Abt. B, 507–578, Stuttgart.

Woollard, G. P. (1960). Seismic crustal studies during the I.G.Y., 2. Continental prograı *Trans. Am. Geophys. Union*, 41, 351–355.
Zeil, W. (1964). *Geologie von Chile*, Gebrüder Borntraeger, Berlin.

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